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Effect of Soil Physical Factors on Methyl Iodide and Methyl Bromide

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Abstract: Production and importation of methyl bromide is scheduled to be banned by 2001. Methyl iodide was evaluated as a possible replacement soil fumigant. The effects of soil moisture, temperature, soil texture and fumigation time on the efficacy of methyl iodide for the control of two common weeds, *Abutilon theophrasti* and *Lolium multiflorum*, were characterized and compared with those of methyl bromide. The optimal soil moisture for methyl iodide to kill both weed species in sandy soils was 14% water content (w/w). Greater efficacy was obtained when the temperature during fumigation was above 20°C. Compared to methyl bromide, the efficacy of methyl iodide was more consistent in different soils. Time to 100% mortality of weeds was 24 h for methyl iodide fumigation and 36 h for methyl bromide when 200 μM of fumigant was used. On a molar basis methyl iodide was consistently more effective than methyl bromide across the range of environmental factors tested. In terms of application technology and spectrum of activity, methyl bromide can be directly replaced by methyl iodide. © 1998 SCI

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Key words: soil fumigation; methyl iodide; methyl bromide; soil moisture; soil temperature; soil texture

1 INTRODUCTION

Methyl bromide (bromomethane) is currently the most widely used soil fumigant. However, it has been classified as a Class One ozone depleter. Methyl bromide production and importation are scheduled to be phased out of use by 2001 in the United States, and later in the rest of the world.[1] The impending phase-out, if the pesticide is not replaced by equally effective alternatives, will cause substantial economic losses to many agricultural communities.[2]

Methyl iodide (iodomethane) was recently proposed as a direct replacement for methyl bromide.[3] One distinct advantage of methyl iodide is that it is quickly degraded in the troposphere *via* photolysis and lasts in the atmosphere for only two to eight days, as compared with two years for methyl bromide.[4] As a result, methyl iodide is unlikely to reach the stratosphere to participate in ozone depletion.[3,5] The ozone depletion potential (ODP) of methyl iodide is estimated as less than 0·016, well below the 0·65 ODP of methyl bromide; thus methyl iodide is considered ozone-safe.[1,3] Another difference is that methyl iodide is a liquid below 43°C, whereas methyl bromide is a gas above 4°C. Increased worker safety will result from the handling of a liquid (methyl iodide) rather than a gas (methyl bromide).

Various laboratory and field experiments demonstrated that methyl iodide was generally more effective than methyl bromide in controlling a wide variety of

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soil-borne plant pathogenic fungi, plant parasitic nematodes, and weeds under a specific environmental condition.[3,6–8] However, the activity of fumigants in the soil is influenced by many factors. Several studies have reported on the effects of soil moisture, temperature, soil texture and fumigation time on the performance of methyl bromide as a soil fumigant,[9] but no data are available on methyl iodide. Moreover, it is not known how the performance of methyl iodide compares with that of methyl bromide under the range of environmental conditions known to occur in commercial fumigation. The answer is crucial to evaluating methyl iodide as a possible substitute for methyl bromide and determining the application conditions. The objective of this study was to characterize the effects of soil moisture, temperature, soil texture and fumigation time on the performance of methyl iodide as compared with methyl bromide.

2 MATERIALS AND METHODS

2.1 General procedures

Since weeds are generally more resistant to fumigation than nematodes or most soil-borne plant-pathogenic fungi,[3] a broadleaf species (*Abutilon theophrasti* Medik.) and a grass weed species (*Lolium multiflorum* Lam.) were used in all experiments as general indicators for most soil pests. A single batch of seeds for each species, obtained from Valley Seed Service in Fresno, CA, was used in all experiments. Germination tests demonstrated that more than 95% of the untreated seeds of both weed species germinated.

Except for the soil texture experiments, a 1 : 1 (v/v) potting mix of fir sawdust and top soil (sand 85%, silt 11%, clay 4%; organic content 9·6%; pH 6·2) was used as a culture medium in all other experiments. The potting mix was adjusted to 14% moisture content, except in the soil moisture experiments. All types of soil and potting mix were autoclaved for 30 min (100 kPa and 121°C). Thirty seeds of each species were thoroughly mixed with enough sterilized soil or potting mix to fill a 45-ml clear plastic vial. The vial had been perforated with 16 1-cm-diameter holes to allow for gas exchange.[3] Vials were filled with the soil or potting mix and seed mixtures, placed in a fumigation container[3] and kept at room temperature (25(±1)°C) for 12–15 h to allow the seeds to imbibe water before treatment. Fumigation containers were 1893-ml wide-mouth canning jars. Methyl bromide was chilled in 454-g cans along with the necessary glassware and pipette tips in a portable ice chest with frozen carbon dioxide overnight. This treatment reduced the temperature of the methyl bromide to approximately −56°C with a vapor pressure below 28 kPa. The chemical was poured into a chilled beaker from which it was pipetted into the jars with chilled pipette tips. Methyl iodide was used at room temperature. The fumigants were pipetted into a 0·5 × 2 cm glass evaporating dish near the jar mouth. The jars were sealed immediately with canning lids and rings and placed horizontally on the laboratory bench at room temperature (25(±1)°C).[3] A volume of 0, 1·5, 3, 6, 12 or 24 μl of methyl iodide and 0, 1·25, 2·5, 5, 10 or 20 μl of methyl bromide was added into each of jars so that methyl iodide and methyl bromide had the same molar concentrations at 0, 12·5, 25, 50, 100 and 200 μM, respectively. The fumigation time was two days for all trials, except for the fumigation time experiment. Except for the soil moisture experiment, after fumigation the content of each vial was spread over 9-cm-diameter Petri dishes containing 7 ml of distilled water. The Petri dish plates were sealed with parafilm and incubated in a laboratory at 25(±1)°C. After five days, the number of germinated seeds was counted. Efficacy was expressed as percentage germination inhibition compared with the nonfumigated control.

2.1.1 *Moisture*

The potting mix was adjusted with distilled water to three moisture levels (w/w): 33·8% (saturated), 14·0% (60% field capacity) and 2·0% (air dry). After fumigation, each replicate of the three moisture levels was spread over 9-cm-diameter Petri dishes containing 0, 7 and 12·5 ml of distilled water, respectively, to adjust soil moisture to the equivalent content during the incubation period. This experiment was arranged in a 3 × 6 factorial design, with three soil moisture contents and six fumigation doses.

2.1.2 *Temperature*

Immediately after the fumigant was added to the fumigation container, one set of fumigation containers with each of six fumigation doses was placed in each of five growth chambers maintained at temperatures of 5, 10, 20, 30 or 40(±1)°C with a photoperiod of 12 h and light intensity of 300 μm m^{-2} s^{-1} for 48 h. This experiment was arranged in a 5 × 6 factorial design with five temperatures and six fumigation doses.

2.1.3 *Soil texture*

Soil was collected from the upper 15 cm of the soil profile in four California fields. The location, soil type, percentage of clay, silt, sand, and organic matter and pH, respectively, are shown for each field site and potting mix: Irvine, Sorrento clay loam, 30, 35, 35, 1·15%, 6·1; Bakersfield, fine sand, 4, 8, 88, 0·36%, 5·9; the University of California South Coast Research and Extension Center at Irvine, San Emigdio sandy loam,

12, 75·4, 12·5, 0·45%, 7·2; Coachella Valley, Carsetas loamy sand, 11, 61, 28, 1·2%, 7·3; and the potting mix, 4, 11, 85, 9·6%, 6·2. Samples were passed through a 2-mm-mesh screen, adjusted to 14% moisture content, and stored at 4°C. Prior to treatment, soil samples were autoclaved, cooled to room temperature, and mixed with weed seeds. Fumigation then proceeded as outlined above. This experiment was arranged in a 5 × 6 factorial design with five soil types and six fumigation doses.

2.1.4 Fumigation time

Vials were exposed to methyl iodide or methyl bromide for 0, 6, 12, 24, 48, 60 or 72 h. After fumigation, weed seed germination in each vial was evaluated in Petri dishes. This experiment was arranged in a 7 × 6 factorial design with seven fumigation times and six fumigation doses.

2.2 Data analysis

All experiments were performed twice. A randomized complete block design with four replicates was used for all experiments. Results for the two trials of each experiment were pooled in all cases because the homogeneity of variances was consistently confirmed by the Bartlett test.[10]

A logistic response curve was used to describe the relationships between percentage germination inhibition (y) of weeds and logarithm of the dose rate (z) of fumigants:

$$y = C + \frac{D - C}{1 + \exp[b(\log(z) - \log(\mathrm{ED}_{50}))]} \tag{1}$$

where D and C are the upper and lower limits of the curve, respectively, ED_{50} denotes the dose required to give a response halfway between the upper and lower limits and b is the slope around the ED_{50}.[11,12] EC_{50} was used instead of ED_{50} where the molar concentration of fumigant was considered rather than the dose.[13]

In this study, initial analyses showed that the upper limit of the curve was never significantly different from 100, on the percentage scale used, and the weeds were killed completely at high doses. Therefore, the upper limit of the curve D was set to 100, and the lower limit of the curve C was set to zero.[8,14,15] Thus, the four-parameter logistic model (eqn (1)) was re-parametrized as a two-parameter model:

$$y = \frac{100}{1 + \exp[b(\log(z) - \log(\mathrm{ED}_{50}))]} \tag{2}$$

Curve fitting was performed by nonlinear regression using the method of least squares. All statistical analyses were performed with SigmaStat and Sigmaplot software.[16] To stabilize the variance, arcsin transformation was used for all percentage data.[10] Data were analyzed by the Transform-Both-Sides technique.[11,12,17,18] For all assays, $\lambda = 0{\cdot}25$ was used to transform both sides. A lack-of-fit test was used to determine if the model adequately described data.[19]

The relative potency of methyl iodide, as compared with methyl bromide, was calculated by using the formula: relative potency = methyl bromide EC_{50}/methyl iodide EC_{50}. If the ratio was greater than 1, then methyl iodide was more effective than methyl bromide.[11,13] The significance in differences between logistic curves was analyzed using the confidence interval approach.[20,21]

3 RESULTS

3.1 Effect of moisture

When soil moisture content was 2%, neither methyl bromide nor methyl iodide completely killed either weed species; for *A. theophrasti*, the highest fumigant dose caused less than 25% seed mortality (Fig. 1). Efficacy of either fumigant was greatest in soil containing 14% moisture, followed by soil containing 33·8% moisture (Fig. 1). For example, the EC_{50} values of methyl iodide for *A. theophrasti* were 28·8 μM at 14% water content and 34·8 μM at 33·8% water content; the EC_{50} values of methyl iodide for *L. multiflorum* were 21·1 μM at 14% water content and 41 μM at 33·8% water content, respectively.

For each of three soil moisture contents, methyl iodide caused greater mortality than methyl bromide for either weed species (Fig. 1). The relative potencies of methyl iodide, as compared with methyl bromide, at the 50% control level, were greater than 1·00 for all three water contents, indicating that methyl iodide was more effective than methyl bromide, on a molar basis, under all soil moisture contents tested (Table 1). For both *A. theophrasti* and *L. multiflorum*, there were no differences in the slopes of the dose-response curves between methyl iodide and methyl bromide at any soil moisture content (Table 1). However, the EC_{50} values of methyl iodide for *A. theophrasti* and *L. multiflorum* at 14% and 33·8% moisture content were significantly less than those of methyl bromide (Table 1). It appears that *A. theophrasti* was more sensitive than *L. multiflorum* to the effect of water content during fumigation with methyl iodide or methyl bromide.

3.2 Effect of temperature

Increasing the temperature during fumigation increased the efficacy of both fumigants for both weed species

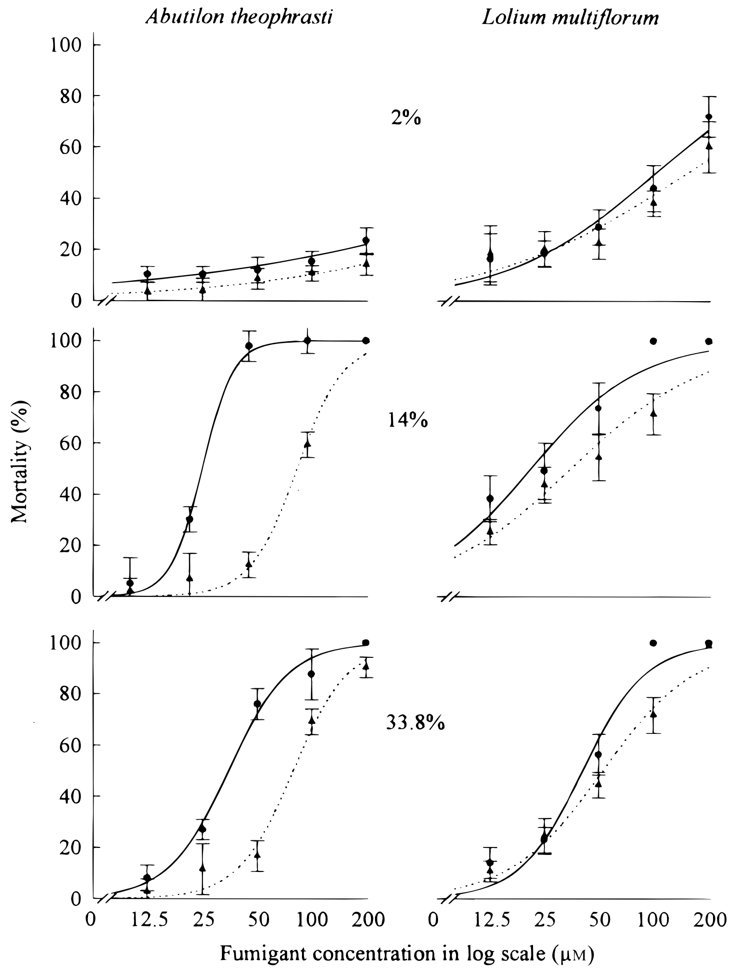

Fig. 1. Effect of soil moisture on the performance of methyl iodide and methyl bromide as soil fumigants, expressed as percentage weed seed mortality. Observations from two trials were pooled because variances were homogenous based on Bartlett's test. (●) and (▲) represent the mean of eight replicates for methyl iodide and methyl bromide treatment, respectively. The solid and dotted lines represent the predicted curves for methyl iodide and methyl bromide treatment, respectively.

(Fig. 2). For methyl iodide, the correlation coefficients between the temperatures and the EC_{50} values were −0·97 for *A. theophrasti* and −0·96 for *L. multiflorum;* the negative correlation indicates that as temperature rises, less methyl iodide is required to kill 50% of the weeds. The greatest EC_{50} was required at 5°C. As compared with the efficacy with 5°C treatment, methyl iodide at 40, 30, 20 and 10°C was 5·3, 4·3. 3·1 and 1·1 times more efficient for the control of *A. theophrasti* and 10·2, 2·8, 2·1 and 1·2 times more efficient for the control of *L. multiflorum*, respectively. A similar trend was observed for methyl bromide fumigation.

For individual temperature treatments, the methyl iodide dose-response curve for *A. theophrasti* at 5 or 10°C was parallel to the methyl bromide dose-response curve, as indicated by the similar slopes (the *b* parameter in Table 2), suggesting that the rate of change in mortality as molar concentration increased was similar between both fumigants. However, the EC_{50} values of methyl iodide at 5 and 10°C were significantly lower than those of methyl bromide; methyl iodide was 1·59 and 1·82 times more potent than methyl bromide for *A. theophrasti* at each of these temperatures (Fig. 2, Table 2). For the temperature treatments above 20°C, the slope of the methyl iodide dose-response curve was significantly greater than that of the methyl bromide curve, suggesting that mortality with increasing molar concentration of methyl iodide was greater than that with methyl bromide in these temperature ranges (Table 2). For *L. multiflorum*, the methyl iodide dose-response curves at temperature treatments below 20°C had a similar slope but significantly lower EC_{50} value than the methyl bromide curve, whereas the slope of the methyl iodide dose-response curve at 30 or 40°C was significantly larger than that of the methyl bromide curve (Fig. 2, Table 2).

3.3 Effect of soil texture

Soil texture did not affect the dose-response curves for methyl iodide (Fig. 3). However, it significantly affected the methyl bromide dose-response of both weed species (Fig. 3). For both fumigants, negative correlations were

TABLE 1

Comparison of Parameters of Dose-Response Curves between Methyl Iodide and Methyl Bromide under Different Soil Moisture Contents

Soil moisture (%)	Differences in b[a]						Differences in EC_{50} [a]						Relative potency[b]	
	ABUTH[c]			LOLMU[c]			ABUTH[c]			LOLMU[c]				
	MeI	MeBr	Sign[d]	MeI	MeBr	Sign.[d]	MeI	MeBr	Sign.[d]	MeI	MeBr	Sign.[d]	ABUTH	LOLMU
2	−1·0	−1·3	NS	−2·4	−1·9	NS	4147	4826	NS	103·7	153·3	NS	1·59	2·11
	(0·18)	(0·16)		(0·36)	(0·36)		(3063)	(2326)		(12·5)	(30·6)			
14	−10·6	−8·4	NS	−3·3	−2·7	NS	28·8	88·3	**	21·1	35·0	*	1·82	2·29
	(4·23)	(1·24)		(0·70)	(0·50)		(1·81)	(3·79)		(1·86)	(2·10)			
33·8	−6·0	−6·57	NS	−5·7	−3·9	NS	34·9	79	**	40·9	52·8	*	1·01	1·01
	(0·71)	(1·01)		(1·20)	(0·49)		(1·81)	(2·95)		(1·89)	(1·11)			

[a] Standard errors for parameter *b* (the slope around the EC_{50}) and EC_{50} are shown in parentheses.
[b] Relative potency = methyl bromide EC_{50}/methyl iodide EC_{50}, indicating the relative toxicity of methyl iodide as compared with methyl bromide.
[c] ABUTH = *Abutilon theophrasti*, LOLMU = *Lolium multiflorum*, MeI = methyl iodide, MeBr = methyl bromide.
[d] NS = not significant, * = significant at 5% level, ** = significant at 1% level. The significance was determined by the confidence interval approach.

TABLE 2

Comparison of Parameters of Dose-Response Curves between Methyl Iodide and Methyl Bromide under Different Temperatures During Fumigation[a]

Soil moisture (%)	Differences in b						Differences in EC_{50}						Relative potency	
	ABUTH			LOLMU			ABUTH			LOLMU				
	MeI	MeBr	Sign.	MeI	MeBr	Sign.	MeI	MeBr	Sign.	MeI	MeBr	Sign.	ABUTH	LOLMU
5	−18·2	−20·3	NS	−4·3	−6·5	NS	64·1	108·9	*	36·0	76·1	*	1·59	2·11
	(0·36)	(0·82)		(0·81)	(0·78)		(0·03)	(10·4)		(3·86)	(3·77)			
10	−20·5	−16·8	NS	−4·1	−4·5	NS	59·3	101·9	*	29·3	67·0	*	1·82	2·29
	(2·51)	(1·12)		(0·66)	(0·98)		(1·01)	(3·44)		(2·79)	(8·09)			
20	−12·9	−8·8	**	−3·6	−4·4	NS	21·0	44·9	—	17·0	29·8	*	2·14	1·76
	(0·26)	(0·94)		(0·55)	(0·78)		(0·09)	(1·26)		(1·57)	(2·92)			
30	−8·0	−3·7	**	−5·5	−3·3	*	14·9	39·81	—	12·9	13·5	—	2·68	1·05
	(0·23)	(1·02)		(0·52)	(1·19)		(0·12)	(7·15)		(0·45)	(3·11)			
40	−77·2	−10·2	**	−10·3	−3·5	*	11·4	12·1	—	0·1	3·029	—	1·01	1·01
	(1·66)	(0·08)		(0·02)	(0·70)		(0·01)	(0·01)		(0·01)	(0·95)			

[a] See Table 1 for footnotes.

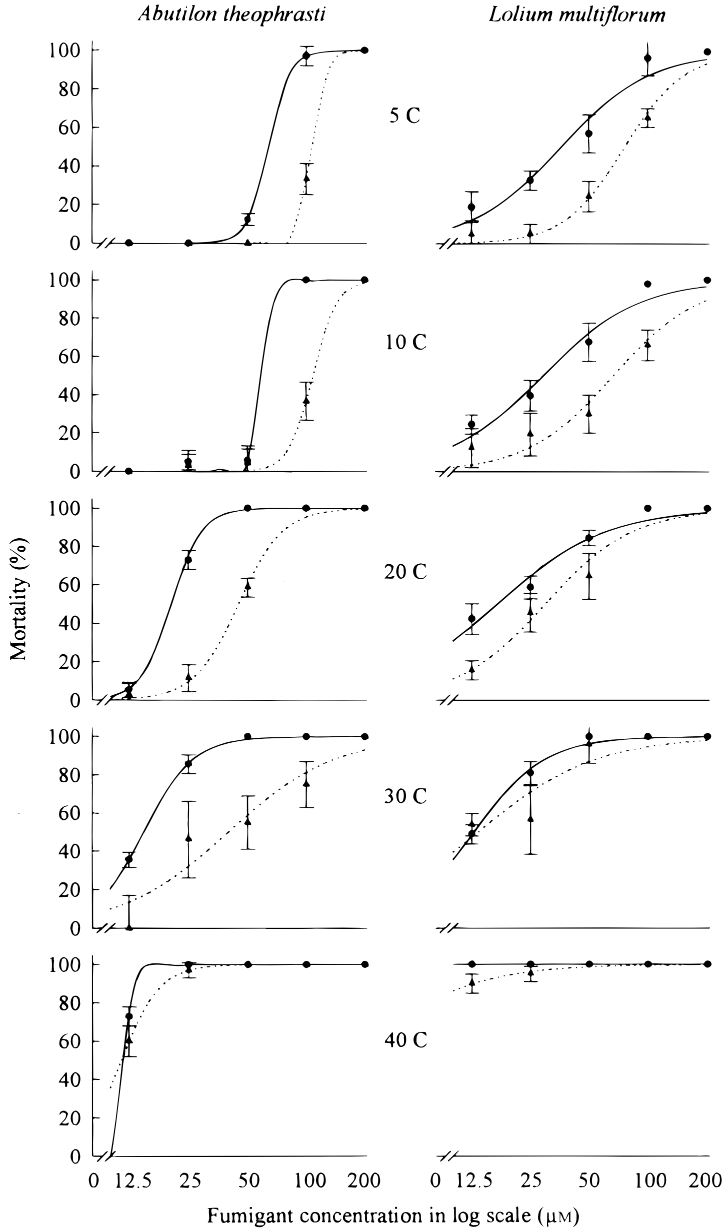

Fig. 2. Effect of temperature on the performance of methyl iodide and methyl bromide as soil fumigants, expressed as percentage weed seed mortality. Observations from two trials were pooled because variances were homogenous based on Bartlett's test. (●) and (▲) represent the mean of eight replicates for methyl iodide and methyl bromide treatment, respectively. The solid and dotted lines represent the predicted curves for methyl iodide and methyl bromide treatment, respectively.

observed between EC_{50} and pH or percentage of sand, whereas positive correlations occurred between EC_{50} and percentage of silt, clay or organic matter (data not shown).

Comparison between methyl iodide and methyl bromide at each of five soil textures for each weed showed no significant differences in the slopes but significant differences in EC_{50} for *L. multiflorum* and significant differences in slopes and EC_{50} for *A. theophrasti*. Thus, methyl iodide was more effective than methyl bromide for the control of both weeds at all soil textures tested (Fig. 3).

3.4 Effect of fumigation time

Seed mortality was first observed after 12 h of fumigation, although the greatest seed mortality at the highest molar concentration was less than 50% for methyl iodide and less than 40% for methyl bromide. Seed mortality of 100% occurred after 24 h of fumigation with methyl iodide and after 36 h with methyl bromide. Increasing the fumigation time increased the efficacy of both fumigants (Fig. 4). Methyl iodide was about 1·50 times more potent than methyl bromide for all fumigation times. The fumigation time at which 50%

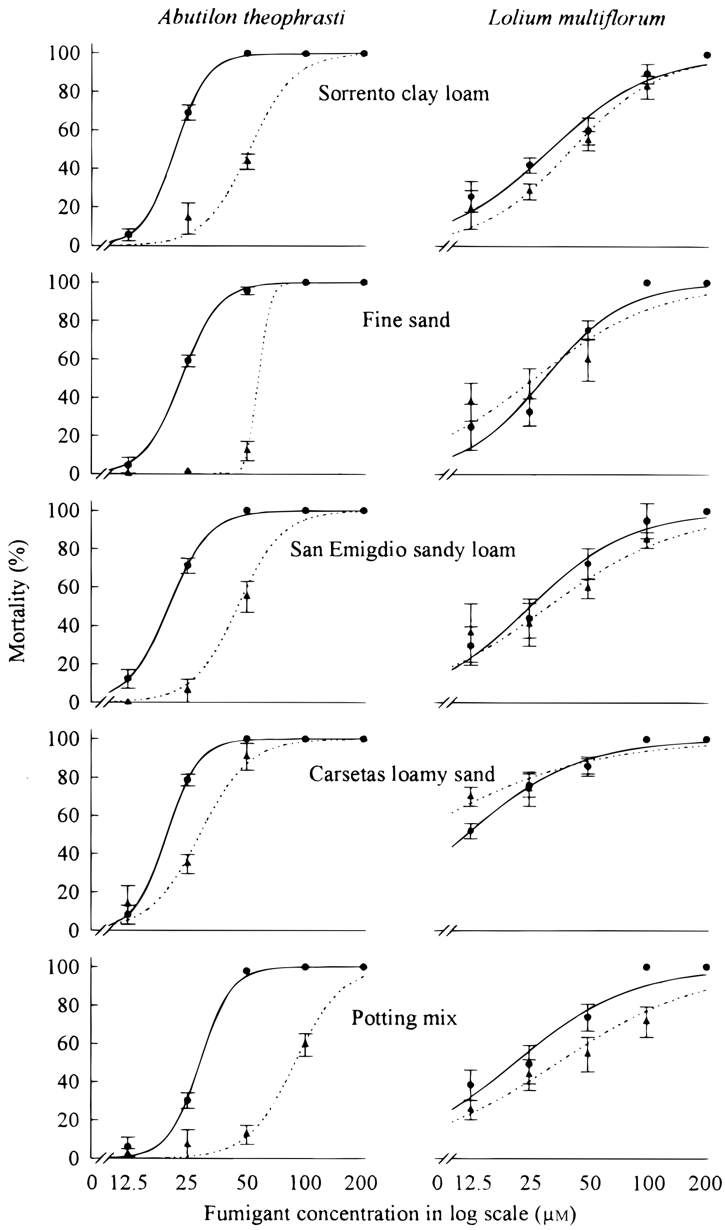

Fig. 3. Effect of soil texture on the performance of methyl iodide and methyl bromide as soil fumigants, expressed as percentage weed seed mortality. Observations from two trials were not pooled because variances were not homogeneous based on Bartlett's test. However, a similar trend was observed in the two trials, and results from one trial are, therefore, presented. (●) and (▲) represent the mean of eight replicates for methyl iodide and methyl bromide treatment, respectively. The solid and dotted lines represent the predicted curves for methyl iodide and methyl bromide treatment, respectively.

of the weed seeds were killed was plotted on a logarithmic scale against log molar concentrations of fumigants in a fashion similar to the dose-response of soil-borne pathogenic fungi to methyl bromide.[22,23] A linear regression analysis of the data points showed a highly significant correlation coefficient (Fig. 5). Similar plots can be made for any EC percentage desired. At a concentration of 100 μM, fumigation times for an EC_{50} were 22·9 and 33·9 h for methyl iodide and methyl bromide, respectively. At a concentration of 200 μM, fumigation times for an EC_{50} were 12·4 and 18·6 h for methyl iodide and methyl bromide, respectively.

4 DISCUSSION

Soil moisture controls the fate of fumigants in their distribution through the soil mass, as well as the physiological activities of the target organisms.[9] As a result, it governs the success or failure of soil fumigation practices. Our data confirm previous recommendations that methyl bromide fumigation for soil-pest control is optimal when water content is somewhat below field capacity.[9] Similar results were obtained for methyl iodide fumigation in this study, although methyl iodide performance was slightly better than methyl bromide,

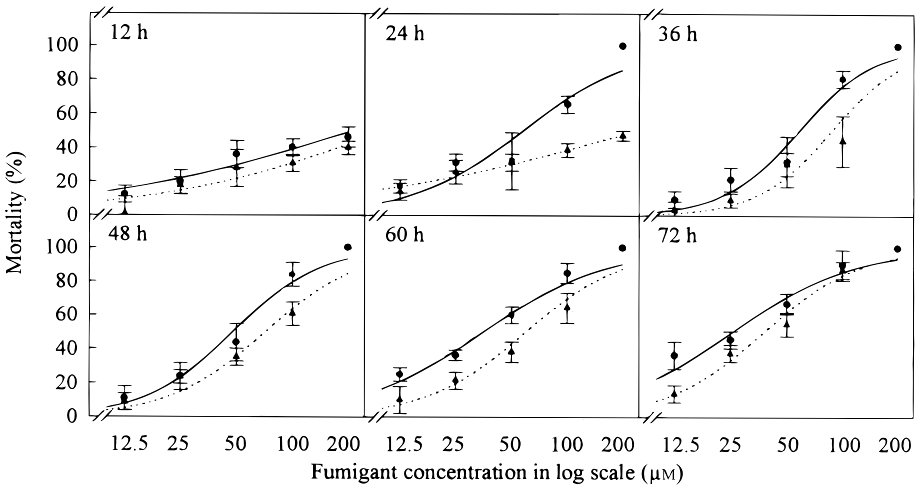

Fig. 4. Effect of fumigation time on the performance of methyl iodide and methyl bromide as soil fumigants for *Lolium multiflorum*, expressed as percentage weed seed mortality. Observations from two trials were not pooled because variances were not homogenous based on Bartlett's test. However, a similar trend was observed in the two trials, and results from one trial are, therefore, presented. (●) and (▲) represent the mean of eight replicates for methyl iodide and methyl bromide treatment, respectively. The solid and dotted lines represent the predicted curves for methyl iodide and methyl bromide treatment, respectively.

even when the potting mixture was extremely dry or wet. Thus, the soil moisture for methyl iodide fumigation should follow the rule for the methyl bromide fumigation, i.e. apply when soil moisture is somewhat below field capacity.

Several studies demonstrated that methyl bromide fumigation to control plant pathogenic fungi and insects improved with increased temperature.[23–25] Our results confirmed this for the control of two weed species. Methyl iodide efficacy also increased with temperature and was higher than that of methyl bromide fumigation within the temperature range tested. Methyl iodide was much more effective than methyl bromide at low temperatures, which suggests wider application area and time with low temperature area and better fumigation

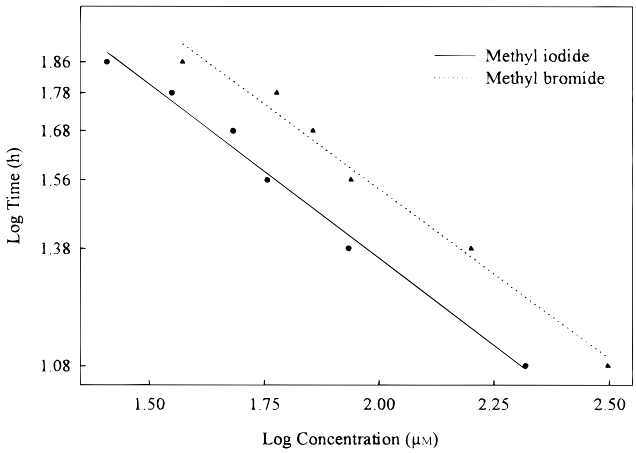

Fig. 5. Fumigation time and dose exposures required to kill 50% of the weed seeds of *Lolium multiflorum*. Model parameters and coefficients for the regression lines: Methyl iodide: $y = 3{\cdot}14 - 0{\cdot}89x$, $r^2 = 0{\cdot}9896$; Methyl bromide: $y = 3{\cdot}27 - 0{\cdot}87x$, $r^2 = 0{\cdot}9824$, where y is log concentration of fumigants and x is log time of fumigation.

results in deeper soil, since the soil temperature decreases with depth.

For methyl bromide fumigation, coarse-textured soils were generally easier to fumigate than fine-textured soils such as clays.[26,27] Methyl iodide performance was more consistent across all soil textures. The sensitivity of weed species to fumigants influenced the performance of the fumigants. *L. multiflorum* is more sensitive than *A. theophrasti*,[8] and methyl iodide performed similarly to methyl bromide for *L. multiflorum*. However, for the less susceptible species, *A. theophrasti*, methyl iodide performed much better than methyl bromide in all the textured soils tested.

Our results showed that two days of fumigation is also sufficient for methyl iodide. The time required to obtain desired control in a range of doses for methyl iodide was shorter than for methyl bromide. Better efficacy for methyl iodide at lower dosage and/or shorter fumigation time is an advantage for deep soil fumigation; thus, methyl iodide would perform better than methyl bromide for fumigation of deep-root plants such as trees.

Our findings demonstrate that methyl iodide is consistently more effective than methyl bromide, on a molar concentration basis, under a range of soil moistures, temperatures, soil textures and fumigation times. Moreover, the response of methyl iodide to each of the above factors followed the results obtained for methyl bromide fumigation. The molecular weight of methyl iodide is about 1·5 times that of methyl bromide. However, the relative potency of methyl iodide, when compared with methyl bromide on a molar concentration basis, is also about 1·5.[8] Comparison on a mass basis would imply that the application of the same number of kilograms of methyl iodide would have a

similar efficacy to methyl bromide. At this time, there is a price advantage for methyl bromide. However, in terms of application technology, environmental impact efficacy, and spectrum of activity, methyl bromide can be directly replaced by methyl iodide.

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REFERENCES

1. Albritton, D. L. & Watson, R. T., Methyl bromide and the ozone layer: A summary of current understanding. In *Montreal Protocol Assessment Supplement*. United Nations Environment Program, Nairobi, Kenya, 1992, pp. 1–19.
2. Ferguson, W. & Padula, A., *Economic effects of banning methyl bromide for soil fumigation*. US Dept. of Agriculture Economic Research Service, Agricultural Economics Report No. 677, 1994.
3. Ohr, H. D., Sims, J. J., Grech, N. M., Becker, J. O. & McGiffen, M. E., Jr, Methyl iodide, an ozone-safe alternative to methyl bromide as a soil fumigant. *Plant Dis.*, **80** (1996) 731–5.
4. Chameides, W. L. & Davis, D. D., Iodine. Its possible role in tropospheric photochemistry. *J. Geophys. Res.*, **85** (1980) 7383–98.
5. Solomon, S., Garcia, R. R. & Ravishankara, A. R., On the role of iodine in ozone depletion. *J. Geophys. Res.*, **99** (1994) 491–9.
6. Becker, J. O., Ohr, H. D., Grech, N. M., McGiffen, M. E., Jr, & Sims, J. J., Evaluation of methyl iodide as a soil fumigant in container and field trials. *Pestic Sci*, **51** (1997).
7. Sims, J. J., Grech, N. M., Becker, O. J., McGiffen, M. E., Jr, & Ohr, H. D., Methyl iodide: a potential alternative to methyl bromide. In *Proceedings of Second Annual International Research Conference on Methyl Bromide Alternatives and Emissions Reductions*, San Diego, 6–8 November 1995, p. 46.
8. Zhang, W. M., McGiffen, M. E., Jr, Becker, J. O., Ohr, H. D., Sims, J. J. & Kallenbach, R. L., Dose response of weeds to methyl iodide and methyl bromide. *Weed Res.*, **37** (1997) 181–9.
9. Munnecke, D. E. & Van Gundy, S. D., Movement of fumigants in soil, dosage response, and differential effects. *Ann. Rev. Phytopathol.*, **17** (1979) 405–29.
10. Gomez, K. A. & Gomez, A. A., *Statistical Procedures for Agricultural Research*, 2nd edn. John Wiley & Sons Inc., New York, 1984.
11. Streibig, J. C., Rudemo, M. & Jensen, J. E., Dose-response curves and statistical models. In *Herbicide Bioassays*, ed. J. C. Streibig and P. Kudsk. CRC Press, Boca Raton, FL, 1993, pp. 29–55.
12. Streibig, J. C., Walker, A., Blair, A. M., Anderson-Taylor, G., Eagle, D. J., Friedlander, H., Hacker, E., Iwanzik, W., Kudsk, P., Labhart, C., Luscombe, B. M., Madafiglio, G., Nel, P. C., Pestemer, W., Rahman, A., Retzlaff, G., Rola, J., Stefanovic, L., Straathof, H. J. M. & Thies, E. P., Variability of bioassays with metsulfuron-methyl in soil. *Weed Res.*, **35** (1995) 215–24.
13. Kleier, D. A. & Gardner, G., Quantitative structure activity relationships: adding value to herbicide bioassay. In *Herbicide Bioassays*, ed. J. C. Streibig and P. Kudsk. CRC Press, Boca Raton, FL, 1993, pp. 75–98.
14. Bartley, M. R., Assessment of herbicide selectivity. In *Herbicide Bioassays*, ed. J. C. Streibig and P. Kudsk. CRC Press, Boca Raton, FL, 1993, pp. 57–74.
15. Ascard, J., Effects of flame weeding on weed species at different developmental stages. *Weed Res.*, **35** (1995) 397–411.
16. Kuo, J., *SigmaPlot 4.1 Beginner's Guide*. Jandel Scientific, Corte Madera, CA, 1990.
17. Carroll, R. J. & Ruppert, D., *Transformation and Weighting in Regression*. Chapman and Hall, New York, 1988.
18. Rudemo, M., Ruppert, D. & Streibig, J. C., Random-effect models in non-linear regression with applications to bioassay. *Biometrics*, **45** (1989) 349–62.
19. Weisberg, S., *Applied Linear Regression*, 2nd edn John Wiley & Sons Inc., New York, 1985.
20. Neter, J., Wasserman, W. & Kutner, M. H., *Applied Linear Statistical Models*, 2nd edn. Irwin, Homewood, IL, 1985.
21. Rawlings, J. O., *Applied Regression Analysis: A Research Tool*. Wadsworth and Brooks, Belmont, CA, 1988.
22. Munnecke, D. E., Bricker, J. L. & Kolbezen, M. J., Dosage response of *Phytophthora cinnamomi* to methyl bromide. *Phytopathology*, **64** (1974) 1007–9.
23. Munnecke, D. E., Bricker, J. L. & Kolbezen, M. J., Comparative toxicity of gaseous methyl bromide to ten soil-borne phytopathogenic fungi. *Phytopathology*, **68** (1978) 1210–16.
24. Gandy D. G. & Chanter D. O., Some effects of time, temperature of treatment, and fumigant concentration on the fumicidal properties of methyl bromide. *Ann. Appl. Biol.*, **82** (1976) 279–90.
25. Kenaga, E. E., Time, temperature, and dosage relationships of several insecticide fumigants. *J. Econ. Entomol.*, **54** (1961) 537–42.
26. Goring, C. A. I., Physical aspects of soil in relation to the action of soil fungicides. *Ann. Rev. Phytopathol.*, **5** (1967) 285–318.
27. McKenry, M. V. & Thomason, I. J., 1,3-Dichloropropene and 1,2-dibromoethane compounds: I. Movement and fate as affected by various conditions in several soils. II. Organism–dosage–response studies in the laboratory with several nematode species. *Hilgardia*, **42** (1974) 393–438.